The Path to Discovery of the Pentaquark: an Exotic Baryon

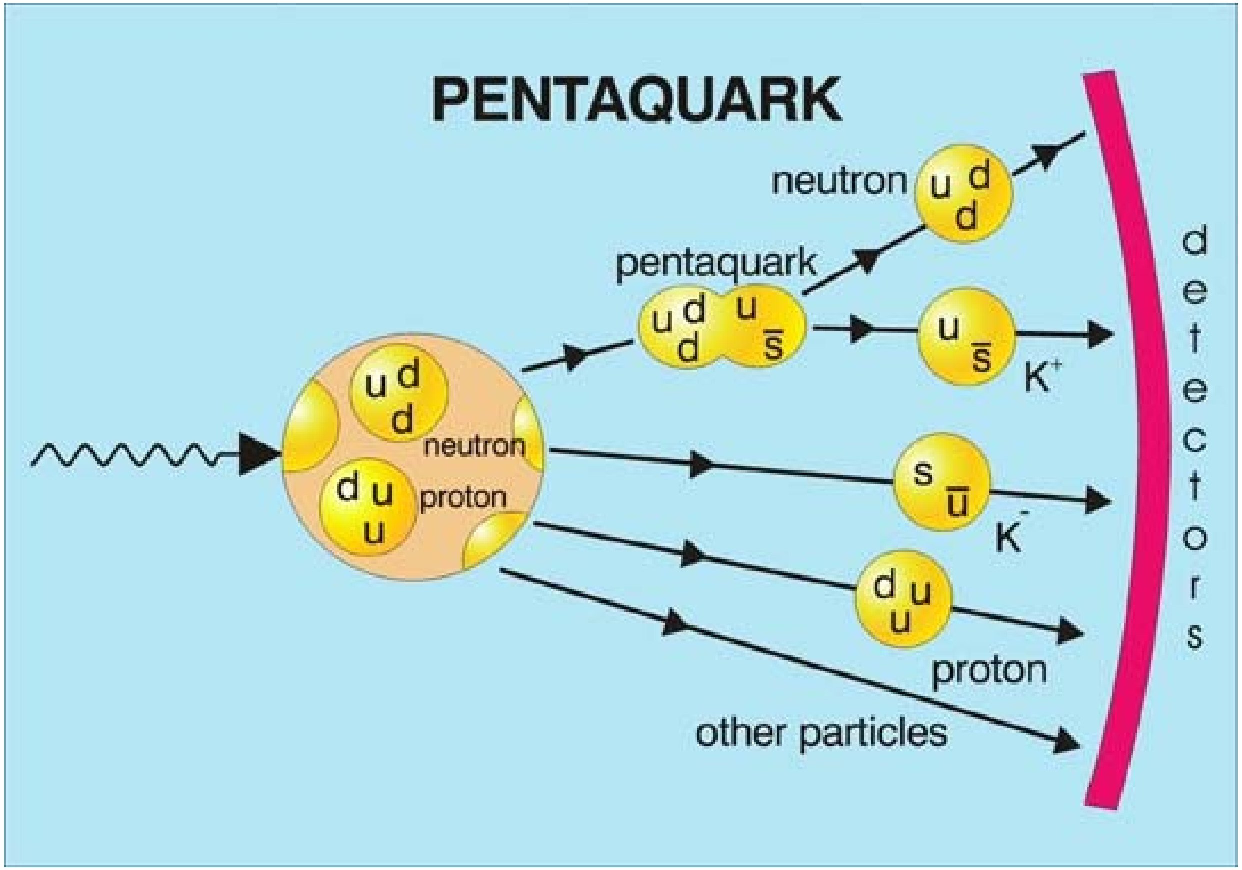
Announcements from LEPS (Japan), ITEP (Russia), CLAS (USA), and ELSA (Germany), provide evidence for the existence of an exotic baryon, a pentaquark with strangeness S=+1, called the Θ^+.

Ken Hicks, Ohio University

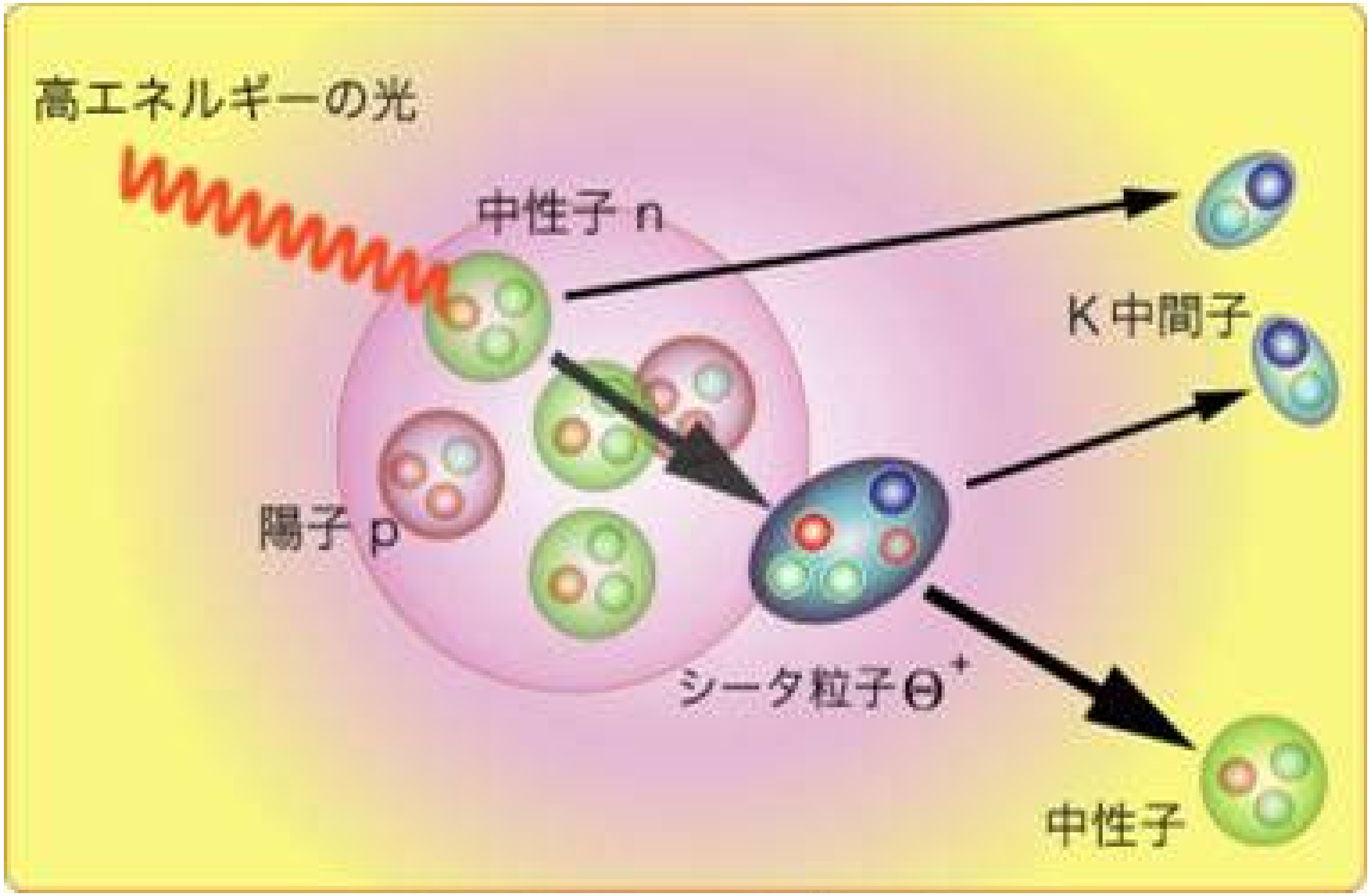
Media Interest

- The pentaquark discovery received wide media coverage:
- Newspapers (July, 2003):
  - New York Times, USA Today, L.A. Times, Boston Globe, Cleveland Plain Dealer, Dallas Morning News, Washington Times, Richmond Times, MSNBC (web), and others…
  - Le Figaro (Paris), Allgemeine Frankfurter (Germany), Times of India, HARRETZ (Israel), Italy, Netherlands, and many newspapers in Japan.
- Magazines:
  - US News & World Report, The Economist, Discover Magazine, Science, Nature, Physics World (IOP), Cern Courier…
- The reason? In part, because the idea is simple to explain.

Media Graphic (from the AIP)



Media Graphic (from the JPS)



Historical Bias Against S=+1 Baryons

(PDG 1986; Phys. Lett. B170, 289)

The evidence for strangeness +1 baryon resonances was reviewed in our 1976 edition,[1] and more recently by Kelly[2] and by Oades.[3] Two new partial-wave analyses[4] have appeared since our 1984 edition. Both claim that the P_{13} and perhaps other waves resonate.

However, the results permit no definite conclusion- the same story heard for 15 years. The standards of proof must simply be much more severe here than in a channel in which many resonances are already known to exist. The general prejudice against baryons not made of three quarks and the lack of any experimental activity in this area make it likely that it will be another 15 years before the issue is decided.

Outline

- What is the pentaquark?
  - How was it predicted by theory?
  - Why is it a new kind of particle?
- Experimental evidence (since October 2002):
  - LEPS (4.6 σ, peak at mass = 1.54 GeV)
  - ITEP (4.5 σ, peak at mass = 1.539 GeV)
  - CLAS (5.5 σ, peak at mass = 1.542 GeV)
  - SAPHIR (4.8 σ, peak at mass = 1.540 GeV)
  - NEW: WA21…ν scattering (6.7 σ, 1533 +/- 5 MeV)
- Theorists response to the pentaquark 'discovery'
- What next in experimental investigation?

A short review…

FERMIONS

matter constituents
spin = 1/2, 3/2, 5/2,...

Leptons spin = 1/2		
Flavor	Mass GeV/c²	Electric charge
ν_e electron neutrino	$< 7 \times 10^{-9}$	0
e electron	0.000511	–1
ν_μ muon neutrino	< 0.0003	0
μ muon	0.106	–1
ν_τ tau neutrino	< 0.03	0
τ tau	1.7771	–1

Quarks spin = 1/2		
Flavor	Approx. Mass GeV/c²	Electric charge
u up	0.005	2/3
d down	0.01	–1/3
c charm	1.5	2/3
s strange	0.2	–1/3
t top (initial evidence)	170	2/3
b bottom	4.7	–1/3

BOSONS

force carriers
spin = 0, 1, 2,...

Unified Electroweak spin = 1	Mass GeV/c²	Electric charge
γ photon	0	0
W^-	80.22	–1
W^+	80.22	+1
Z^0	91.187	0

Strong or color spin = 1	Mass GeV/c²	Electric charge
g gluon	0	0

Sample Fermionic Hadrons					
Baryons qqq and Antibaryons $\bar{q}\bar{q}\bar{q}$					
Symbol	Name	Quark content	Electric charge	Mass GeV/c²	Spin
p	proton	uud	1	0.938	1/2
$\bar{p}$	anti-proton	$\bar{u}\bar{u}\bar{d}$	–1	0.938	1/2
n	neutron	udd	0	0.940	1/2
Λ	lambda	uds	0	1.116	1/2
Ω^-	omega	sss	–1	1.672	3/2

Sample Bosonic Hadrons					
Mesons $q\bar{q}$					
Symbol	Name	Quark content	Electric charge	Mass GeV/c²	Spin
π^+	pion	$u\bar{d}$	+1	0.140	0
K^-	kaon	$s\bar{u}$	–1	0.494	0
ρ^+	rho	$u\bar{d}$	+1	0.770	1
D^+	D^+	$c\bar{d}$	+1	1.869	0
η_c	eta-c	$c\bar{c}$	0	2.979	0

Symmetries and Conservation Laws

- A conservation law implies a symmetry of nature:
  - Conservation of momentum → gauge invariance
  - Conservation of energy → time reversal invariance
- Other conservation principles for particles:
  - Conservation of baryon number → flavor $SU(n)_f$
  - Conservation of strangeness → hypercharge
  - Conservation of isospin → chiral symmetry
- Gell-Mann used these symmetries (and group theory) to develop the quark model.

The Particle Zoo (I)

Baryons ($J^\pi = 1/2^+$)

Name	Lifetime	Mass	Strange	Charge
p	stable	938.3	0	+1
n	stable	939.6	0	0
Λ	3. e-10	1115.	-1	0
Σ^+	1. e-9	1189.	-1	+1
Σ^0	1. e-19	1193.	-1	0
Σ^-	1. e-10	1197.	-1	-1
Ξ^0	3. e-10	1315.	-2	0
Ξ^-	2. e-10	1321.	-2	-1

Is there a pattern here? What about the Λ?

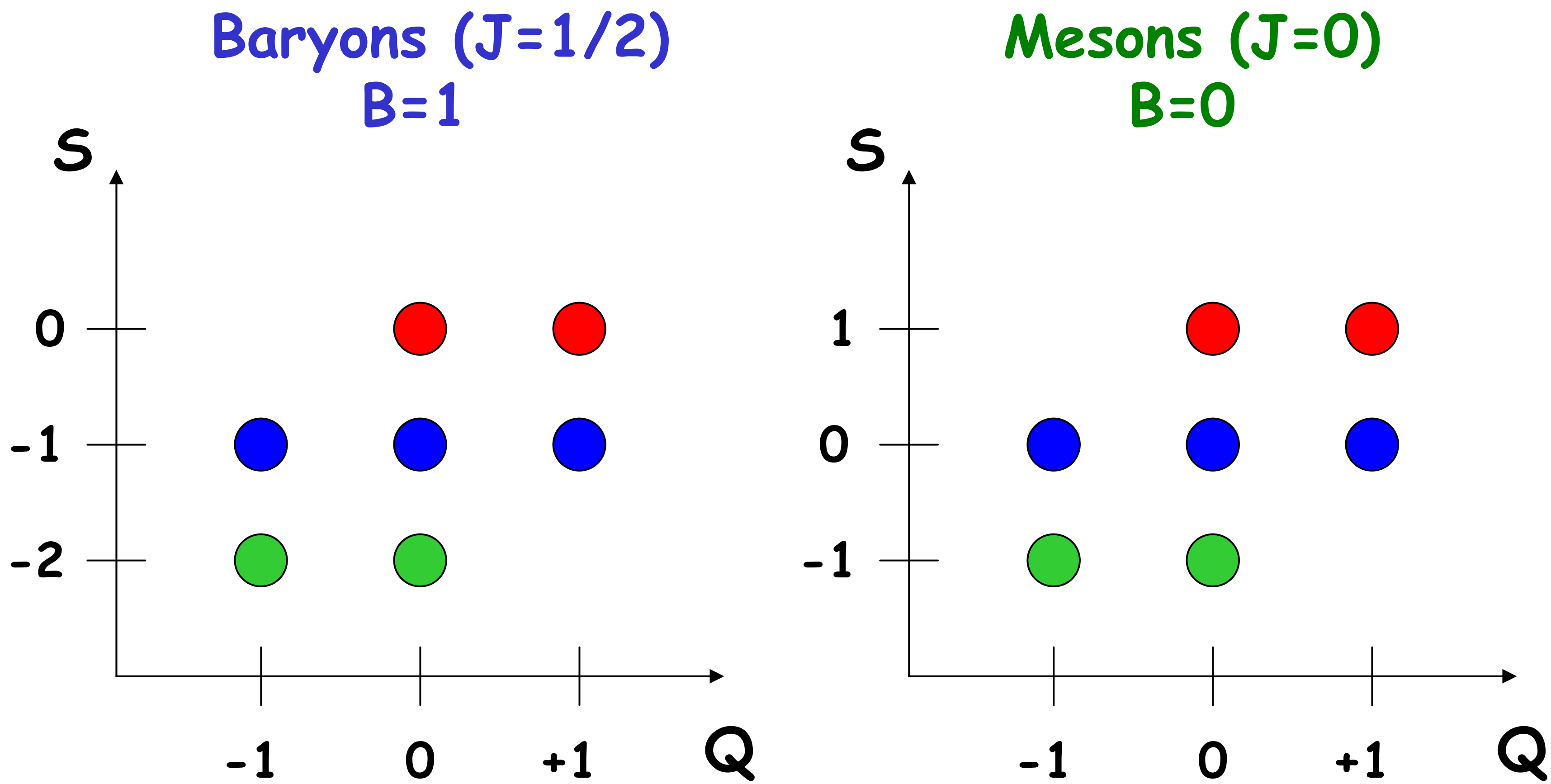
The Particle Zoo (II)

Mesons ($J^{\pi} = 0^{-}$)

Name	Lifetime	Mass	Strange	Charge
K^{+}	1. e-8	493.7	+1	+1
K^{0}_{S}	1. e-10	497.7	+1/-1	0
π^{+}	3. e-8	139.6	0	+1
π^{0}	1. e-16	135.0	0	0
π^{-}	3. e-8	139.6	0	-1
K^{0}_{L}	5. e-8	497.7	-1/+1	0
K^{-}	1. e-8	1321.	-1	-1

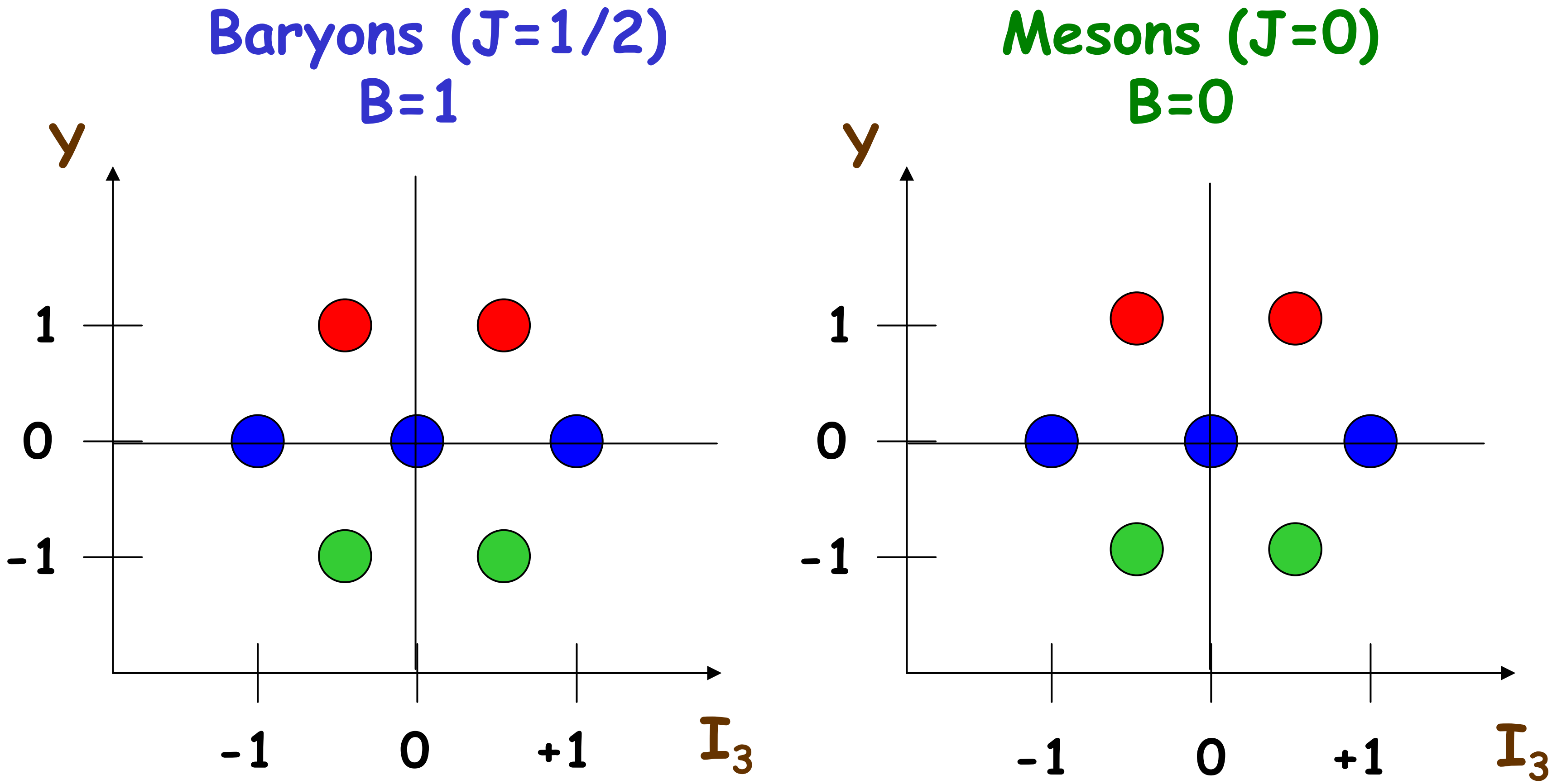
Is this better? How do the K^{0} mesons fit in?

Strangeness vs. Charge



→ To center, define: $Y = B+S$ and $I_3 = Q-Y/2$.

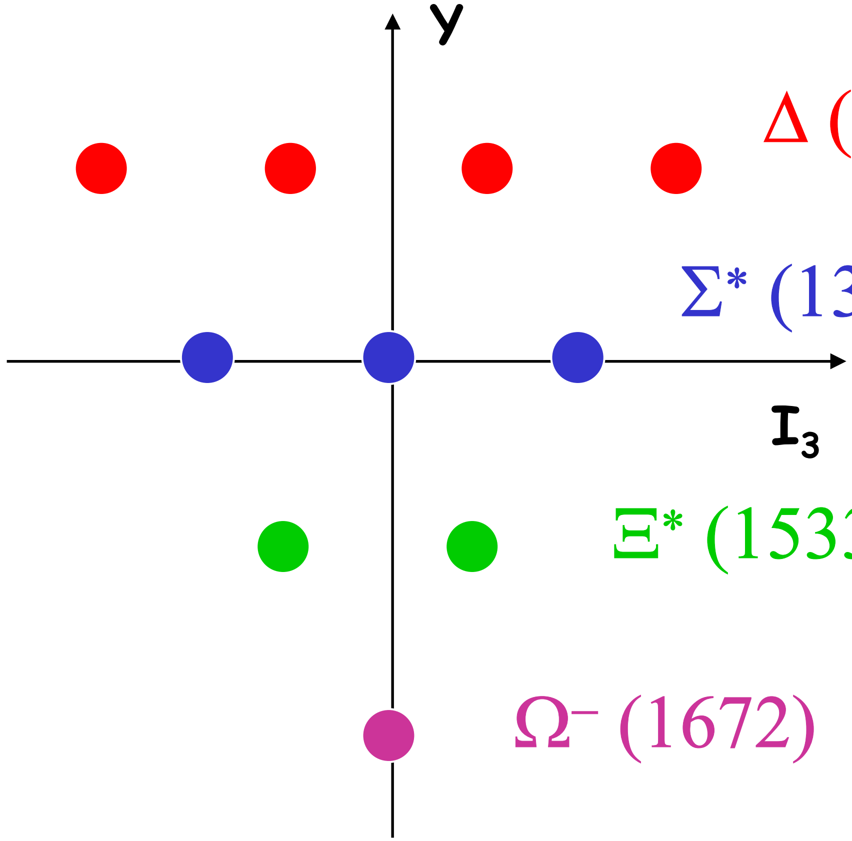
Hypercharge vs. Isospin



→ Now the objects can be treated as QM rotations

The standard baryon decuplet

Baryons (J=3/2)



Δ (1232) **S=0**

Σ^* (1385) **S=-1**

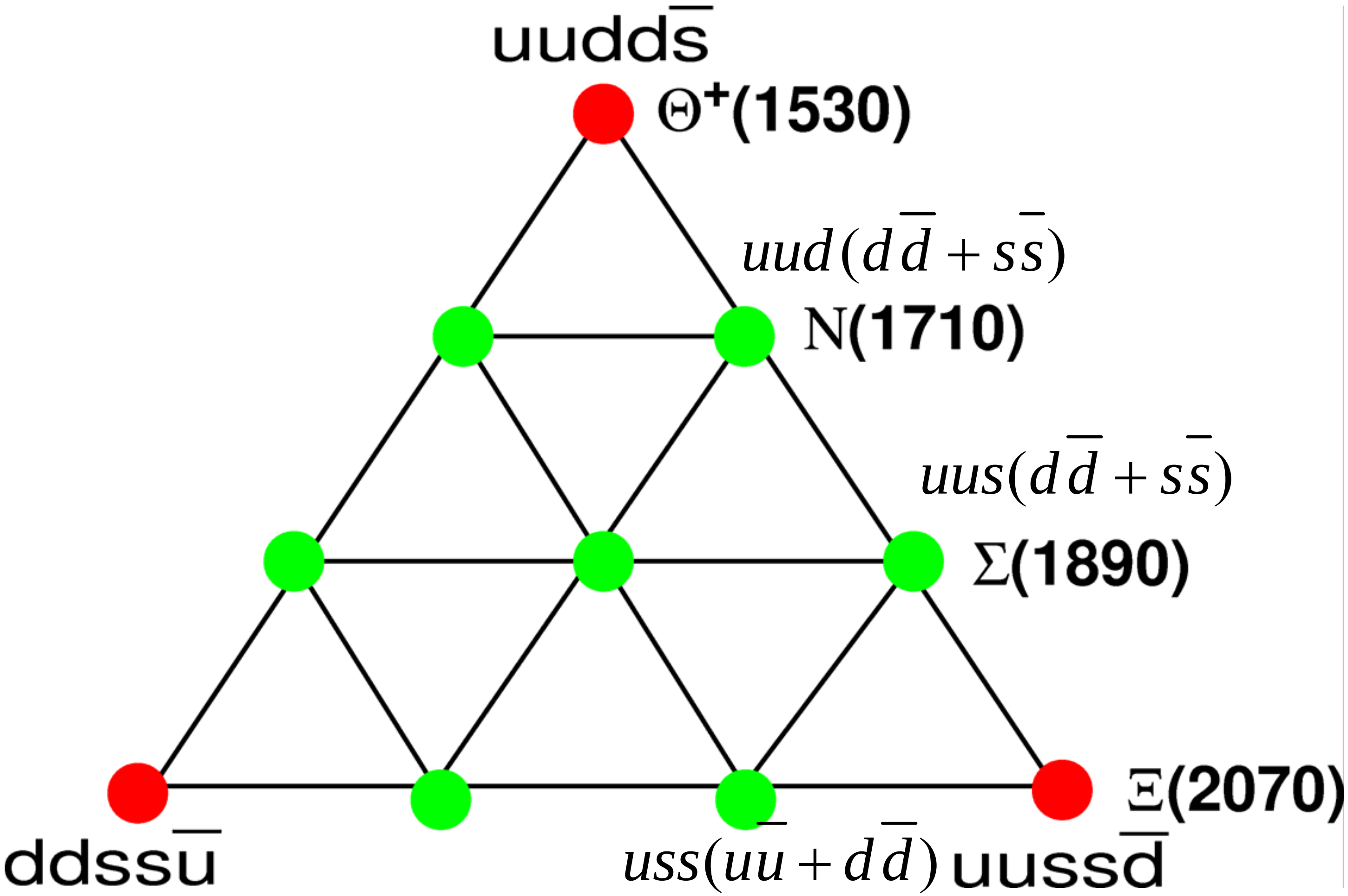
Ξ^* (1533) **S=-2**

Ω^- (1672) **S=-3**

Each unit of strangeness costs about 150 MeV.

The Gell-Mann/Okubo relation: equal mass spacings

The anti-decuplet from the chiral soliton



Parameters of the chiral soliton model

- There are 3 equations and 3 unknowns:
  - The soliton model parameters are α, β and γ. These are related to two "moments of inertia" of rotations in spin and isospin space, and the chiral symmetry breaking.
- Experimental (known) values:
  - Mass splittings of groups, and the in-medium quark condensate $\Sigma = 0.5(m_u+m_d) \langle N|(uu+dd)|N\rangle = 0.045$ GeV.
- Specifically:
  - Octet: $m(\Xi)-m(N) = (\alpha/2)+2\beta+(\gamma/4)$
  - Decuplet: $m(\Sigma^*)-m(\Delta) = (\alpha/8)+\beta-(5\gamma/16)$
  - Anti-decuplet: $m(N^*)-m(\Theta^+) = (\alpha/4)+\beta+(\gamma/8)$
- These mass splittings are satisfied to ~1-2% !

What is the Θ^+ ?

- The Θ^+ is has quark structure ($uudd\bar{s}$):
  - Experiment conserves baryon number and strangeness
- Prediction by D. Diakonov, V. Petrov, and M.Polyakov,
  - Z. Phys. A 359, 305 (1997)
- chiral soliton model: mass = 1530 MeV
  - Θ^+ width predicted ~15 MeV
  - $J^P=1/2^+$ (requires NK^+ orbital L=1)
- Mass fixed by the N* ($J^P=1/2^+$) at mass = 1710 MeV
  - This is the only well-known P_{11} above the Roper resonance
- Similarly, there is a P_{11} state Σ at mass = 1880 MeV
  - Only given "2-star" status by the PDG

Why is the Θ^+ important?

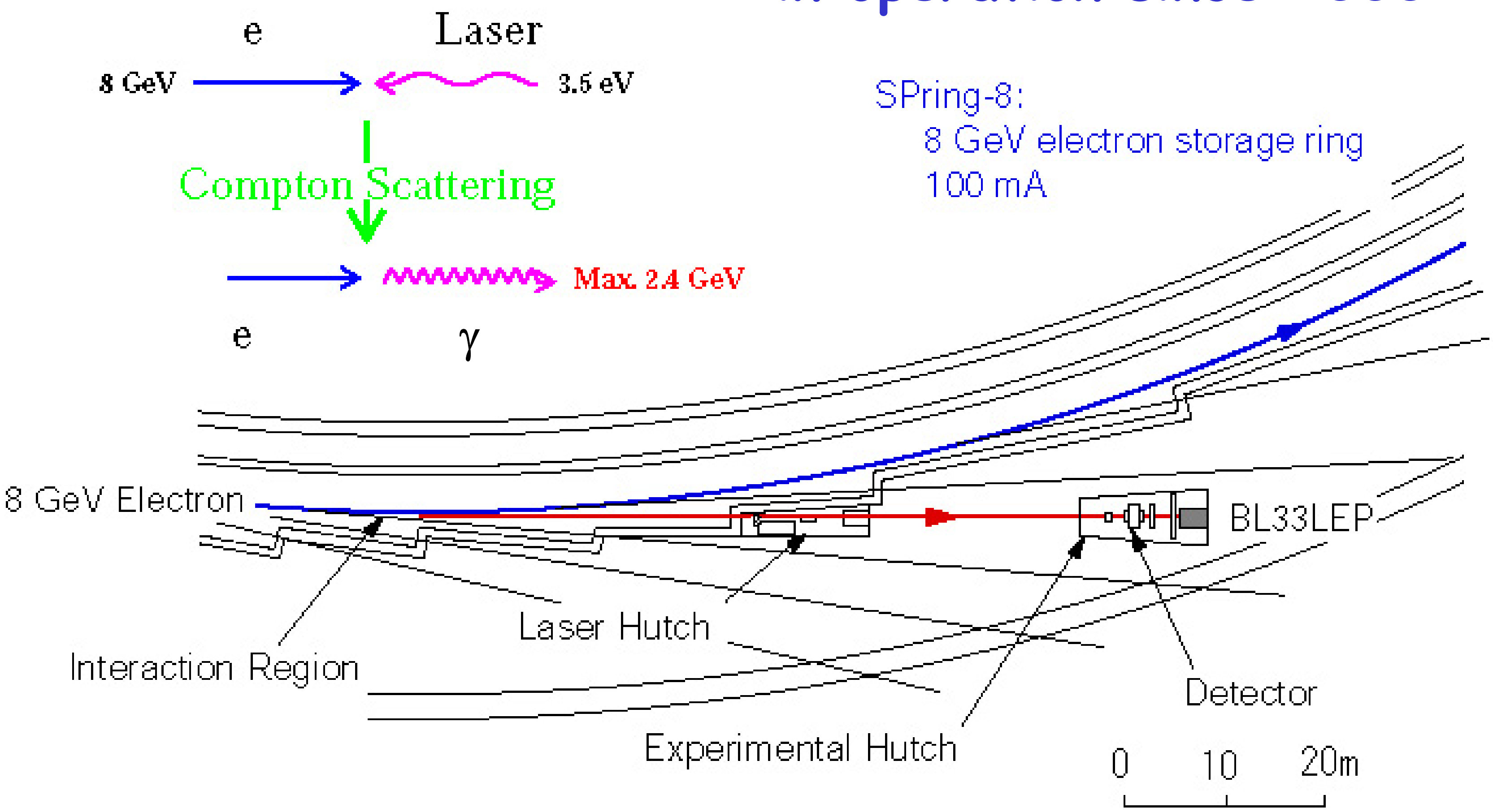
- QCD does not prohibit $q^4\bar{q}$ states, but early searches failed to produce evidence for pentaquarks. This led people to believe that all baryonic matter comes in only one form: 3-quark states.
- The Θ^+, if found, is the first hard evidence of a new class of particle: the pentaquark.
- One of the central activities at Jefferson Lab is to understand N* resonances. Do pentaquarks contribute to the resonance spectrum?

Super Photon ring-8 GeV SPring-8

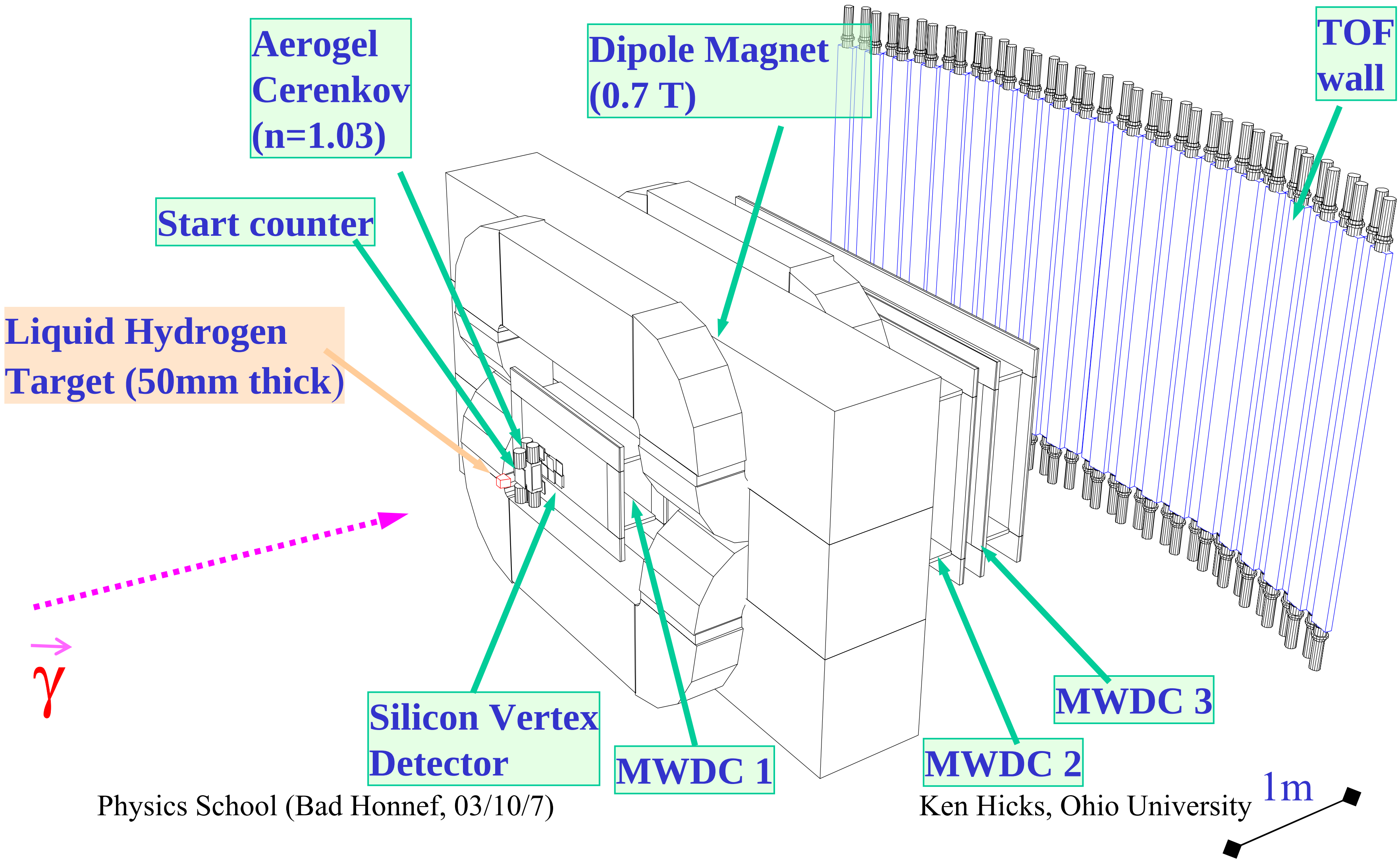
- Third-generation synchrotron radiation facility
- Circumference: 1436 m
- 8 GeV
- 100 mA
- 62 beamlines

Laser Electron Photon facility at SPring-8

in operation since 2000

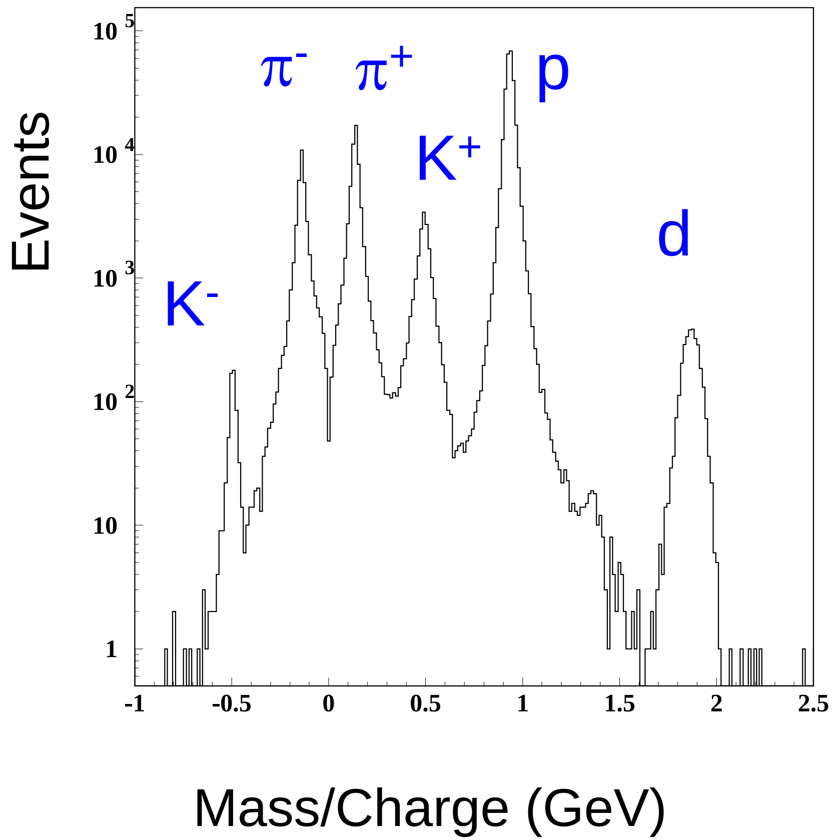


LEPS detector

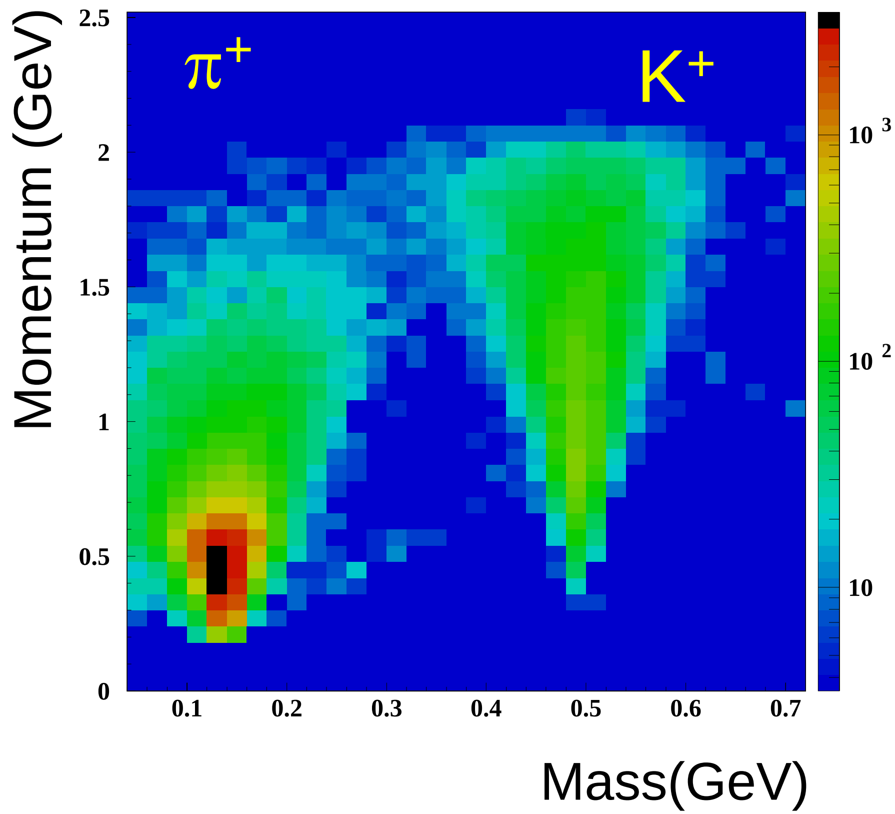


Charged particle identification

Reconstructed mass



K/π separation (positive charge)

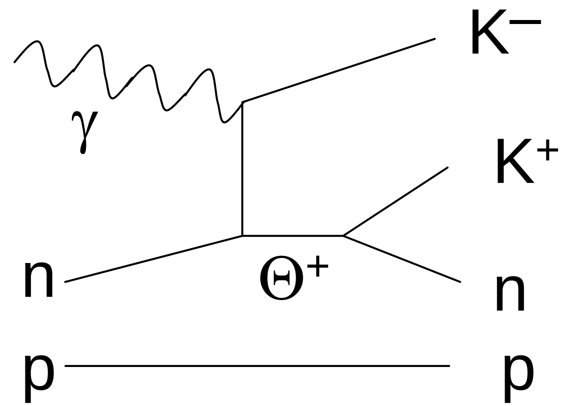


σ(mass) = 30 MeV(typ.) for 1 GeV/c Kaon

Detected nuclear reactions

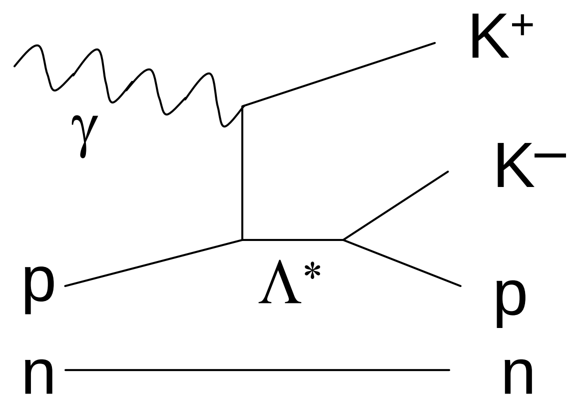
$$\gamma n\,(p) \rightarrow \Theta^{+} K^{-}\ (p)$$

$$\Theta^{+} \rightarrow K^{+} n$$



$$\gamma p\,(n) \rightarrow \Lambda^{*}(1520) K^{+}\ (n)$$

$$\Lambda^{*}(1520) \rightarrow K^{-} p$$



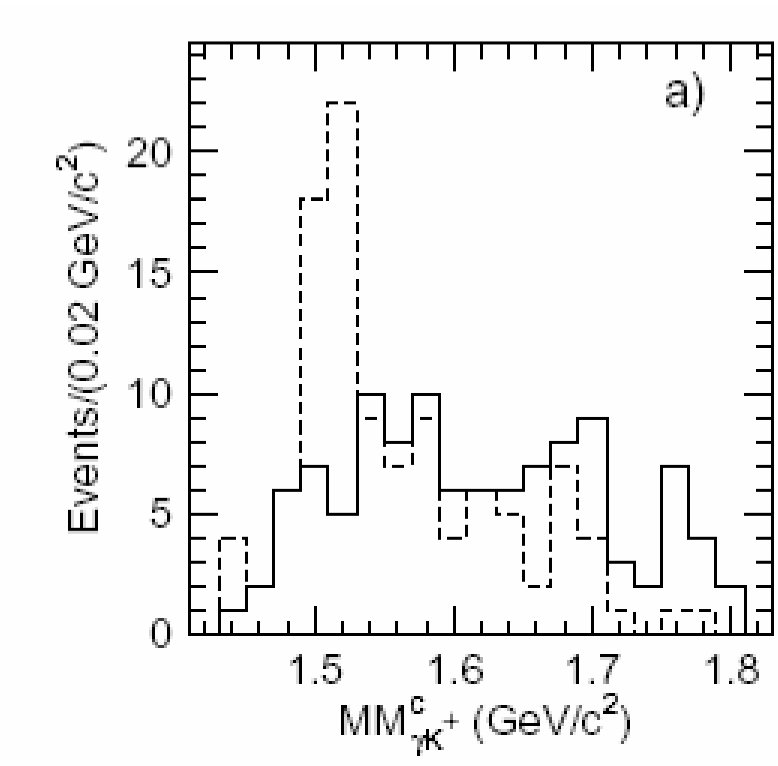
$$\boxed{\gamma N \rightarrow \phi(1020)\, N \rightarrow K^{+} K^{-} N}$$

Θ^+ analysis at LEPS at Spring-8.

LEPS Collaboration (T. Nakano *et al.*), PRL **91**: 012002, 2003; hep-ex/0301020

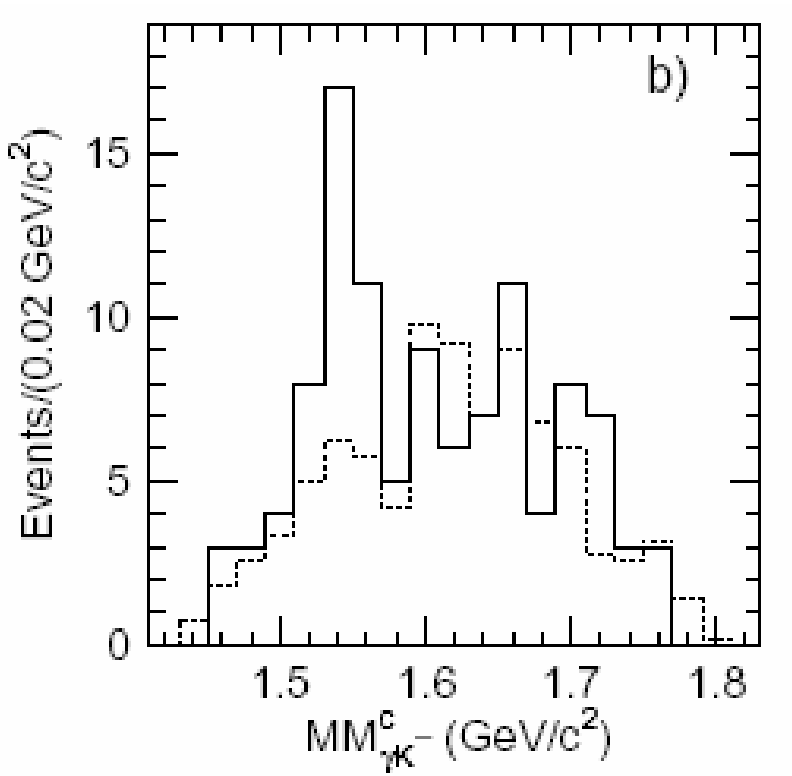
- Look in $\gamma\, ^{12}C \Rightarrow N\, K^- \Theta^+ \Rightarrow N\, K^- K^+ n$
- elementary process: $\gamma n \Rightarrow \Theta^+ K^- \Rightarrow n K^+ K^-$
- Detect K^-, look at missing mass $MM_{\gamma K-}$
- Remove events with energetic protons
- Estimate background from LH_2 target

Λ(1520) from LEPS at Spring-8.



- Make Fermi motion correction:
- $\gamma p \Rightarrow \Lambda(1520)K^+ \Rightarrow K^+(p)K^-$ same nucleon is struck in both cases; know proton.
- Dashed: events where recoil proton detected, shows clear Λ(1520) peak
- Solid: proton veto showing no Λ peak

Observation Θ+ from LEPS at Spring-8.

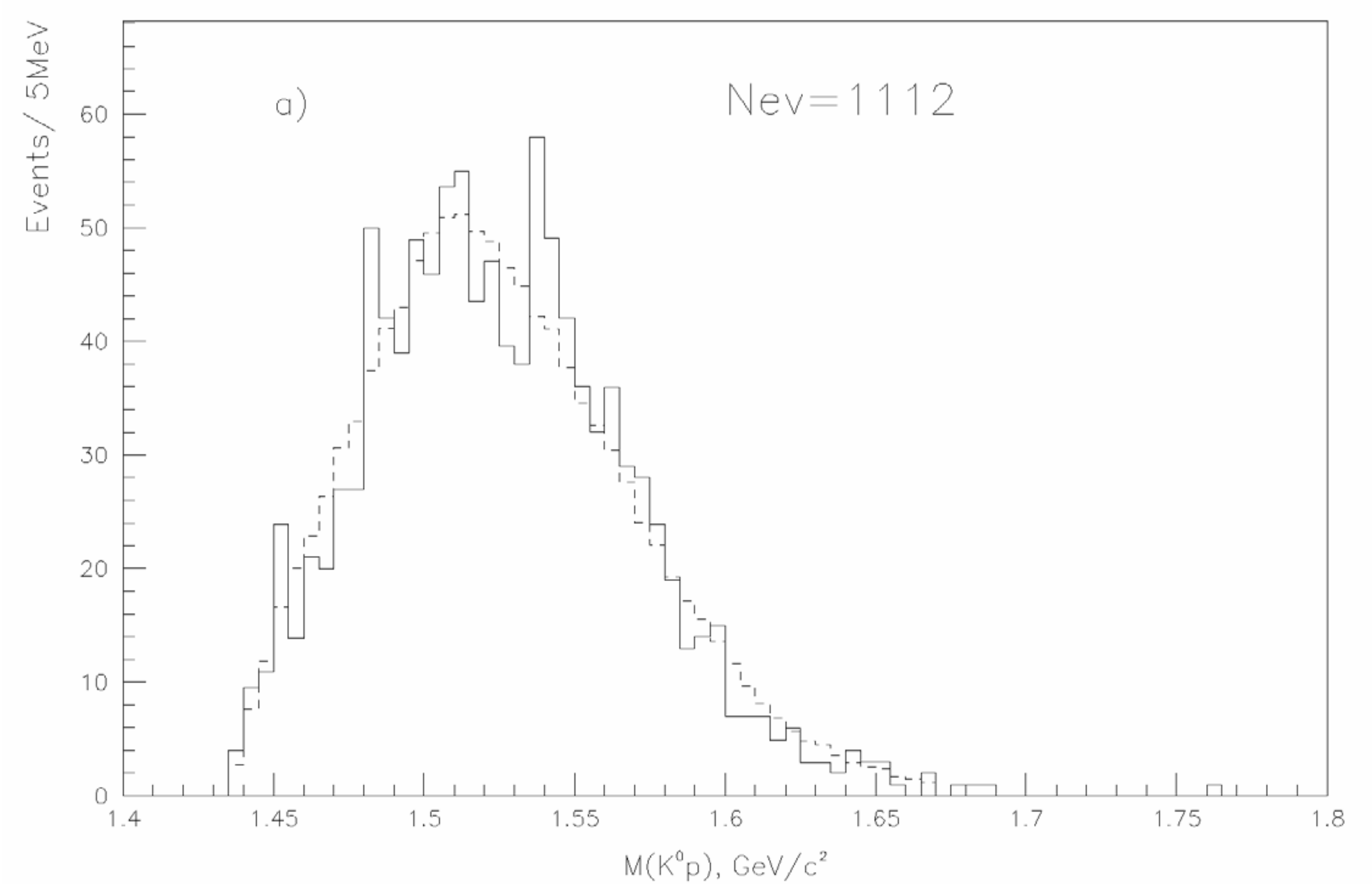


- Apply same Fermi motion correction to $MM_{\gamma K-}$
- Solid: signal sample
- Dashed: background from protons in upstream H_2 target, normalized to signal above 1590 MeV
- 19 +/- 2.8 events above background of 17
- Mass 1540 +/- 10 MeV
- Width < 25 MeV @ 90% CL

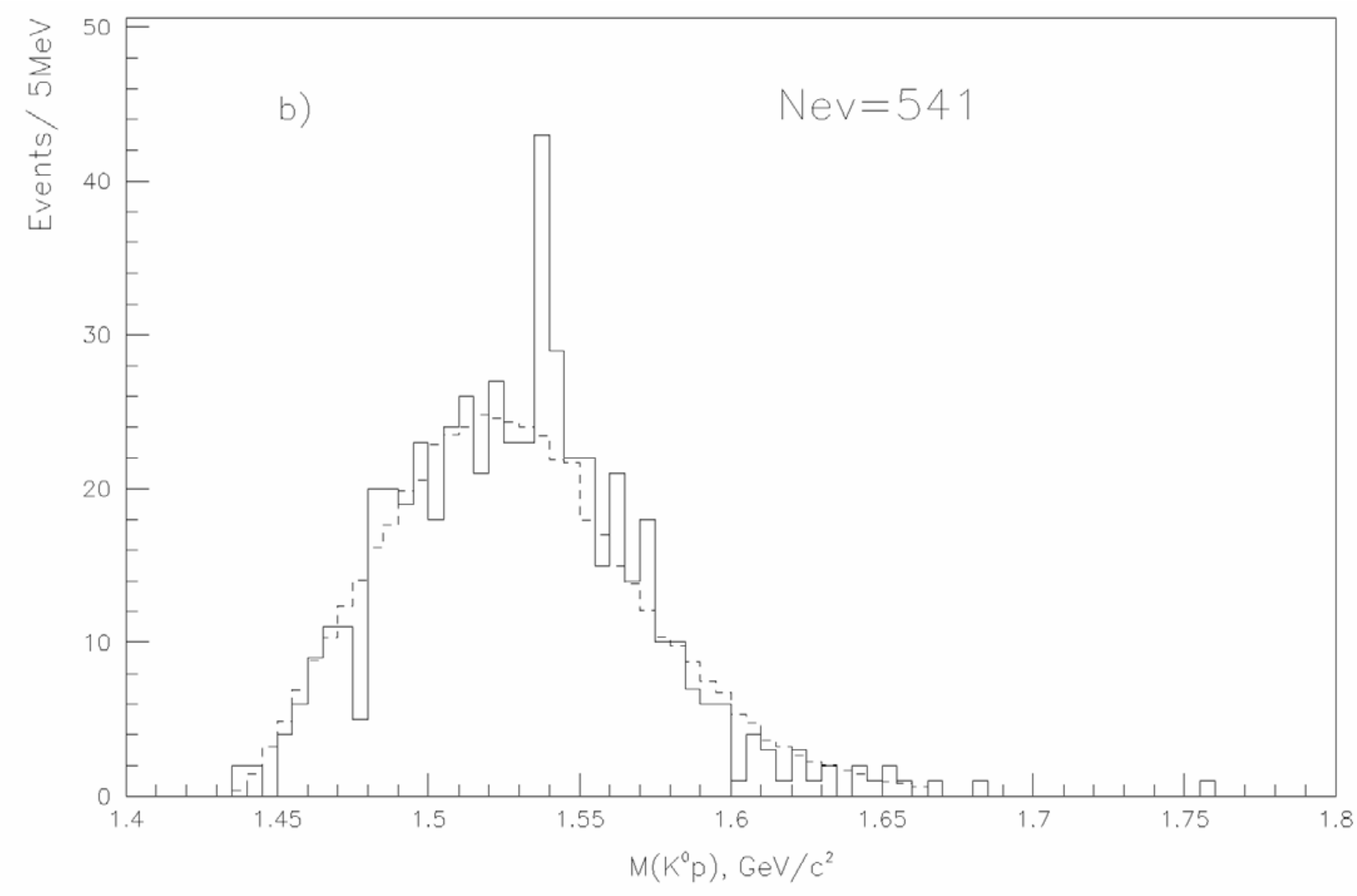
Θ^+ from DIANA@ITEP…

- DIANA Collaboration hep-ex/0304040
- Xe bubble chamber, 850 MeV K^+ beam from proton synchrotron at ITEP
- $K^+ \, Xe \Rightarrow \Theta^+ \, Xe' \Rightarrow (K^0 p) \, Xe'$
  - 1539 +/- 2 MeV, width < 9 MeV (detector resolution), statistical significance 4.4 σ.
- Criticism: not exclusive final state…

All measured events DIANA@ITEP…



…with cuts to suppress p and K^0 reinteractions in Xe nucleus



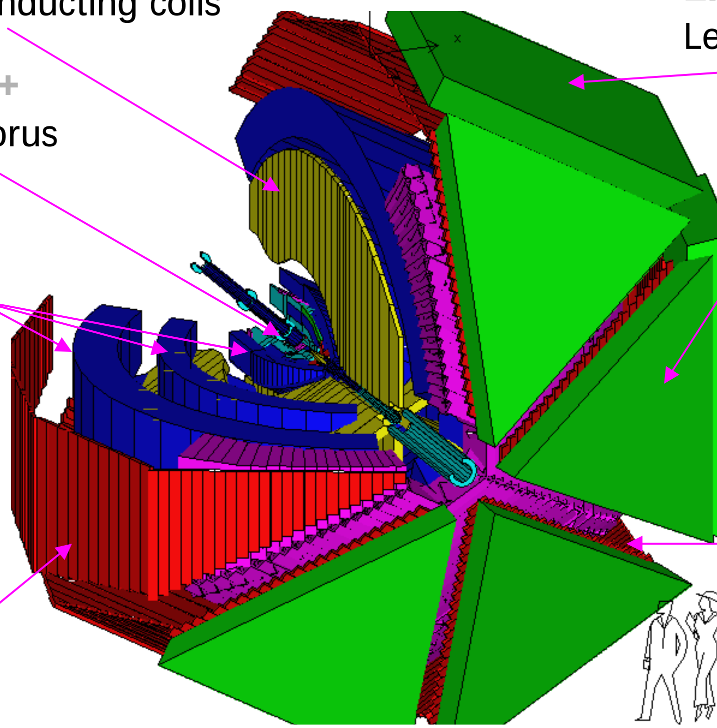
CEBAF Large Acceptance Spectrometer

Torus magnet
6 superconducting coils

Electromagnetic calorimeters
Lead/scintillator, 1296 photomultipliers

Liquid D_2 (H_2)target +
γ start counter; e minitorus

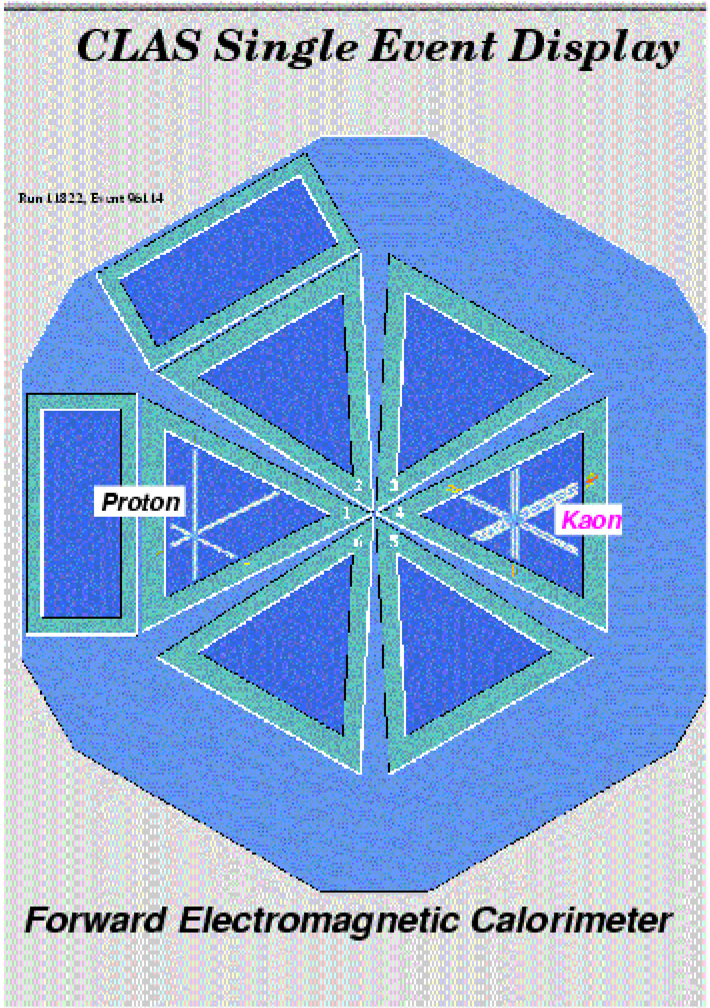
Drift chambers
argon/CO_2 gas, 35,000 cells



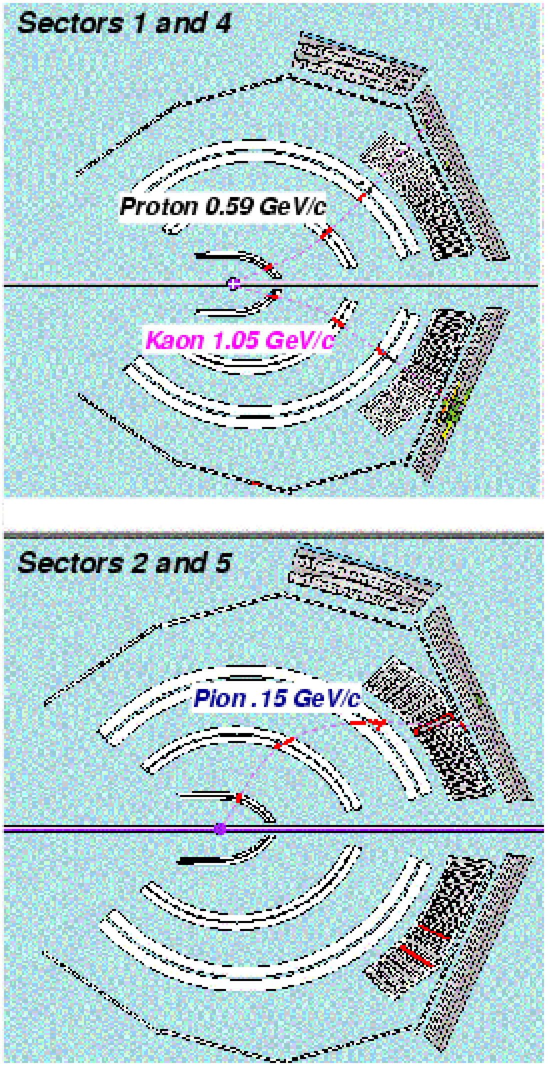
Gas Cherenkov counters
e/π separation, 256 PMTs

Time-of-flight counters
plastic scintillators, 684 photomultipliers

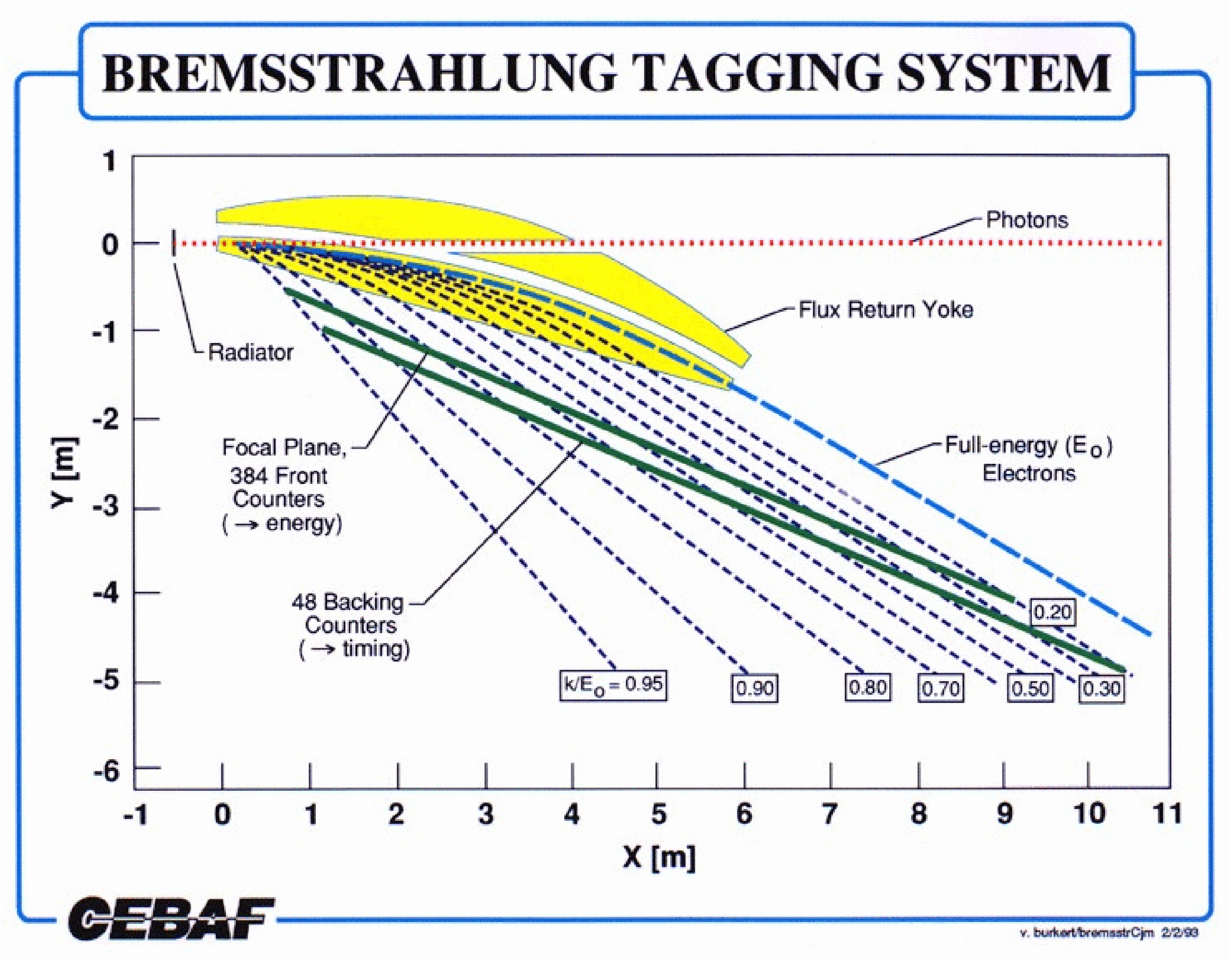
Event detection in CLAS@JLab



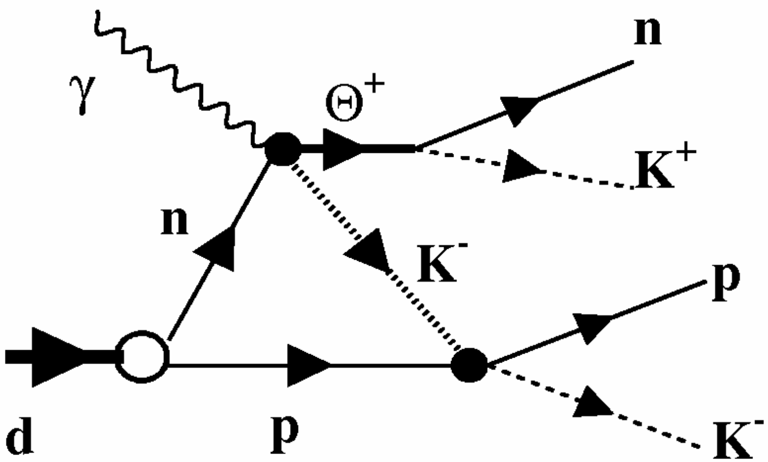
Beam Photon: 1.58 GeV



The CLAS Photon Tagger



Exclusive reaction on deuterium

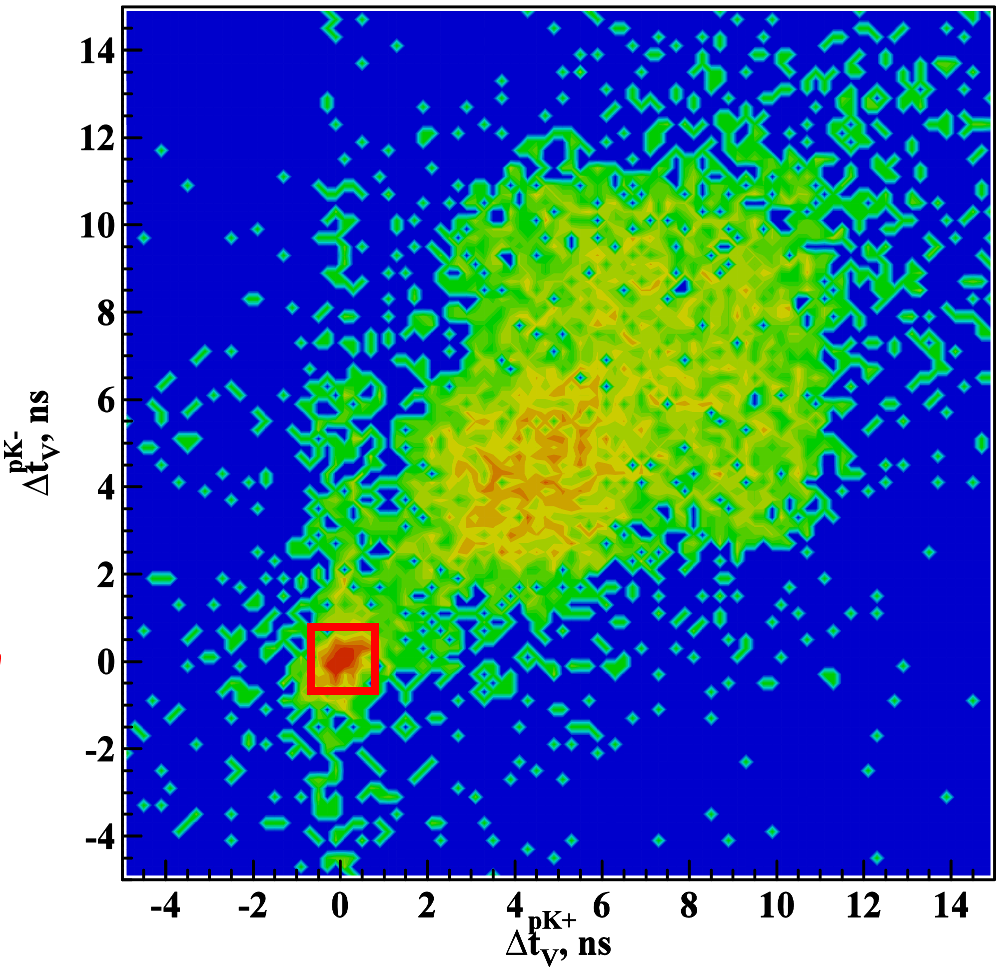


CLAS Collaboration (S. Stepanyan, K. Hicks, *et al.*), hep-ex/0307018

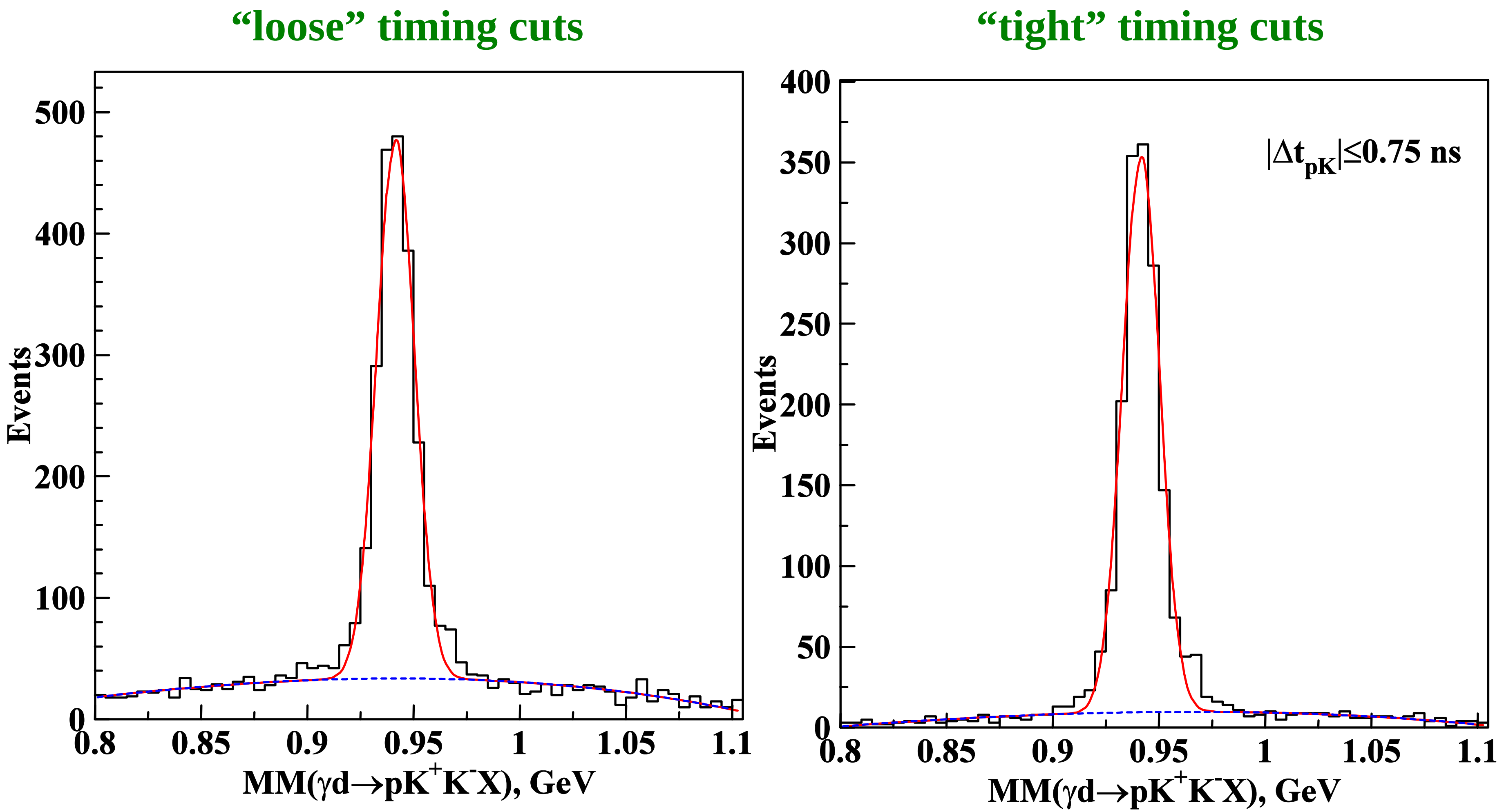
- Requires FSI – both nucleons involved
  - No Fermi motion correction necessary
  - FSI not rare: in ~50% of $\Lambda(1520)$ events both nucleons detected with p>0.2 GeV/c

Time difference for K^-p and K^+p

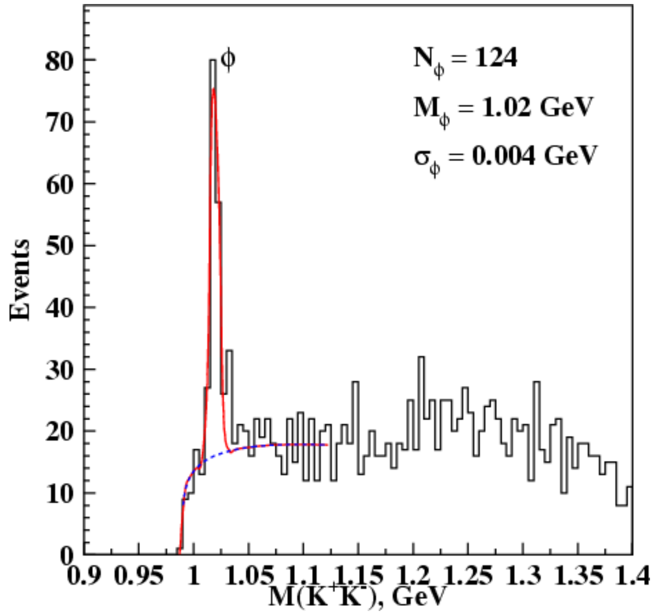
tight timing

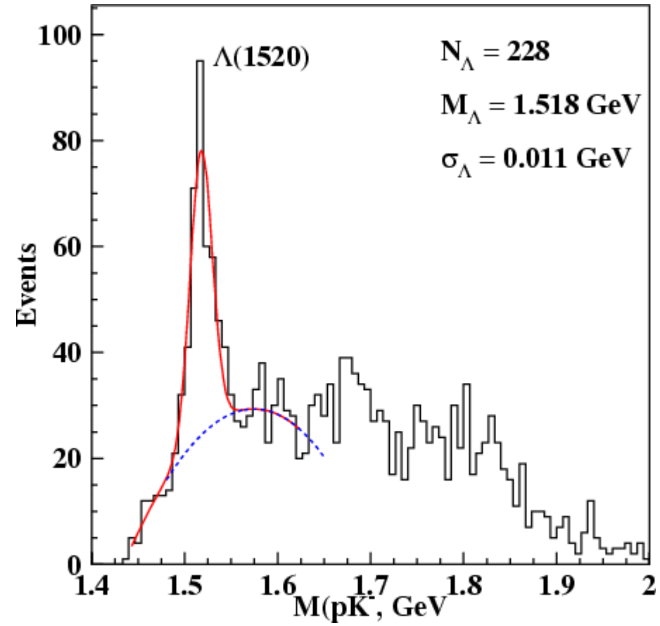


Neutron found via missing mass



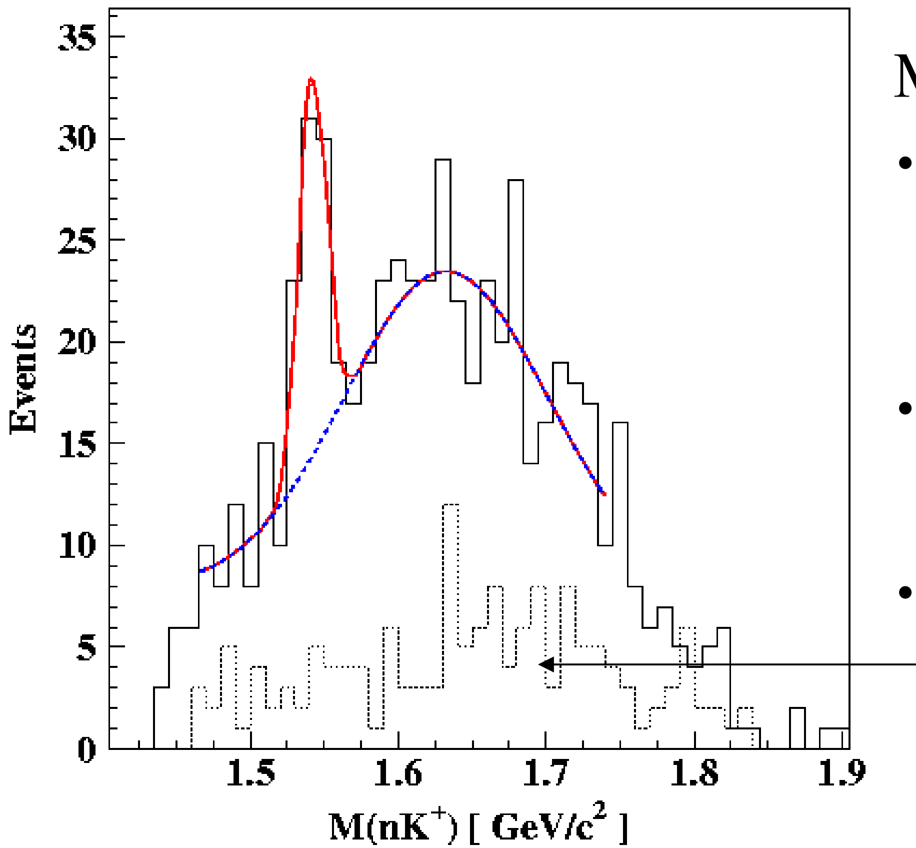
Θ^+: Background Rejection





- Remove events with IM(K^+K^-)→ $\phi(1020)$
- Remove events with IM(pK^-)→ $\Lambda(1520)$
- Limit K^+ momentum due to MC studies $\mathbf{p_{K^+} < 1.0 GeV/c}$

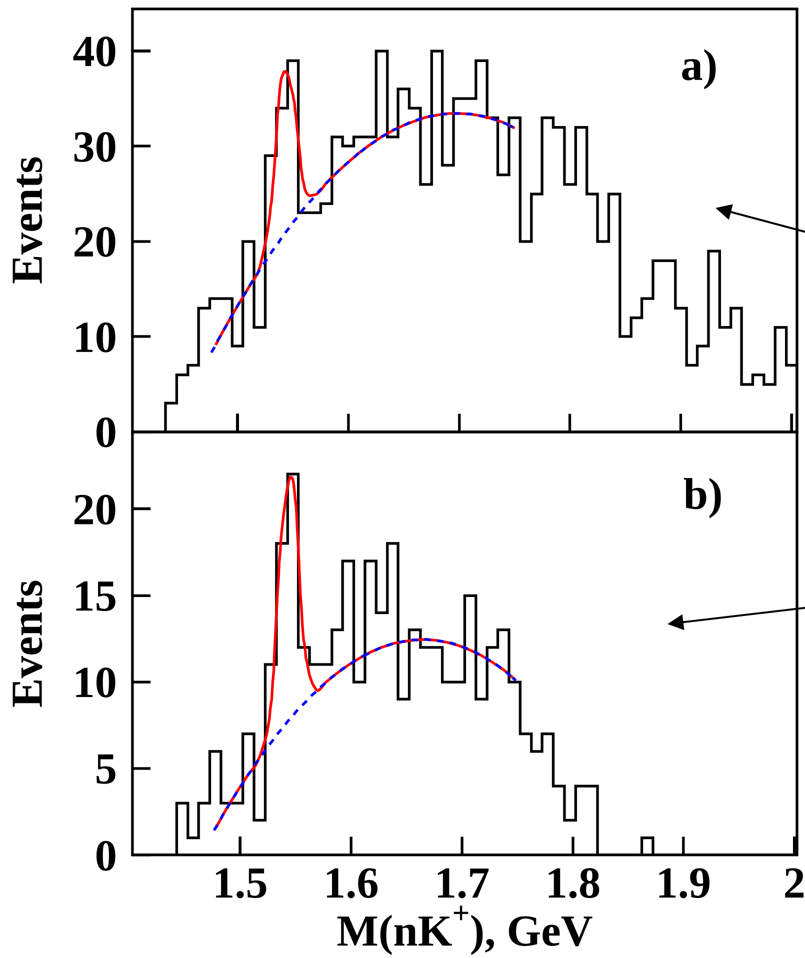
Θ^+ the g2 Exclusive Result



$M(nK^+) = MM(\gamma d \rightarrow pK^- X)$

- ~42 events in the narrow peak at 1542+/-5 MeV with FWHM of 21 MeV/c
- Estimated significance 5.3+/-0.5 σ
- Spectrum of the events associated with $\Lambda(1520)$

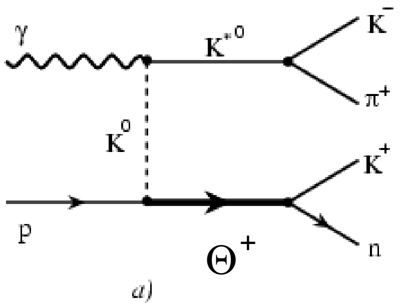
Variations of cuts for the Θ^+ analysis

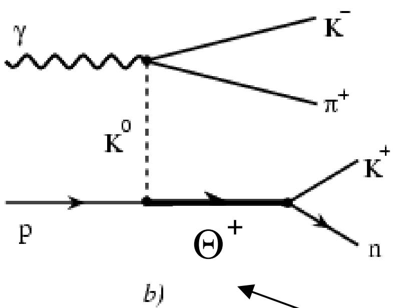


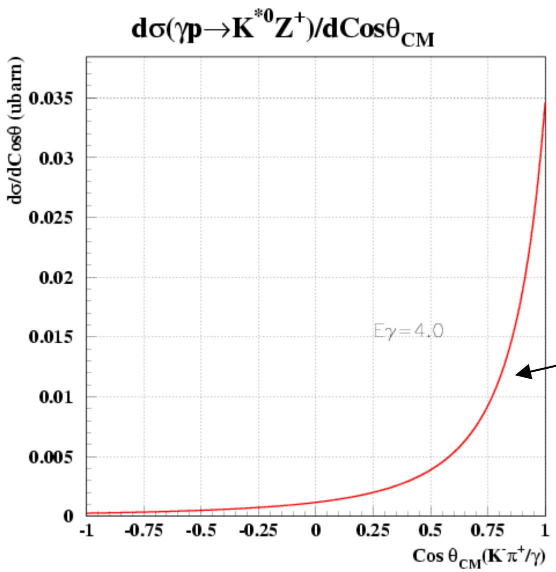
$M(nK^+) = MM(\gamma d \rightarrow pK^- X)$

- a) no longer has cuts on the $\Lambda(1520)$ or on the K+ momentum, giving only a 4.8 σ fit.
- b) has tighter timing cuts, which require that each K+ comes within 0.75 ns of the proton, giving 6.0 σ.

Θ^+ on hydrogen g6 data in CLAS

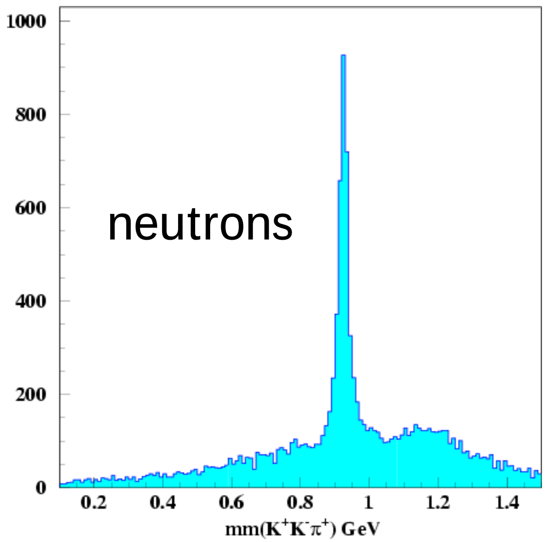


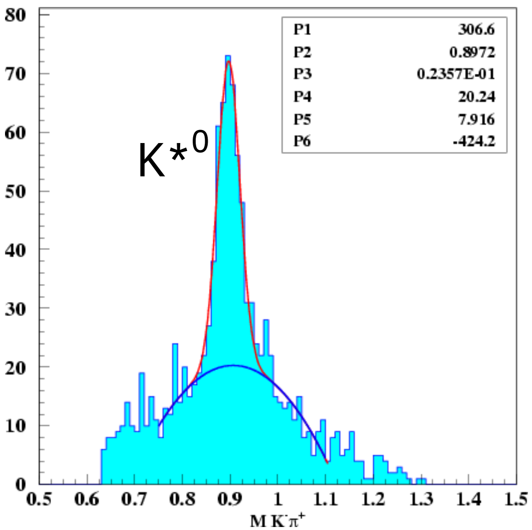




- exclusive channel
  $\gamma p \Rightarrow \pi^+ K^+ K^- (n)$
- Production via *t*-channel K^0 exchange
  - Largest cross section at big cosθ equivalent with small *t* (M. Polyakov)

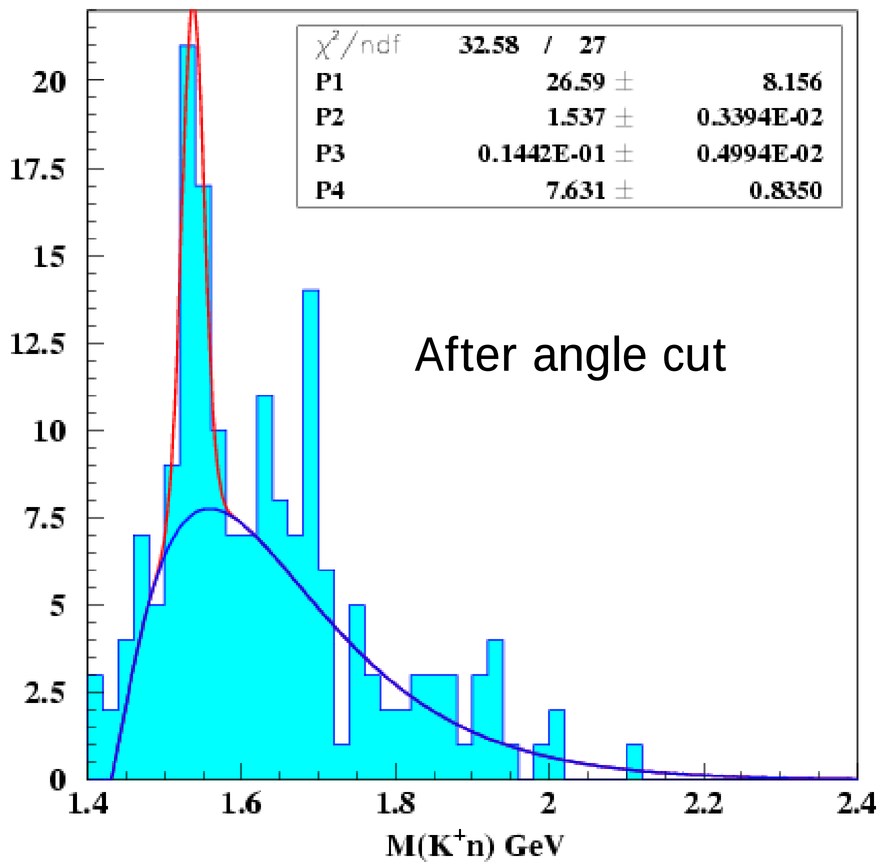
Θ^+: Channel Identification





- Missing mass selects neutrons: $\gamma\, p \rightarrow \pi^+ K^+ K^- X$
- Invariant mass of $\{\pi^+ K^-\}$ selects K^{*0}

Θ^+: CLAS proton target

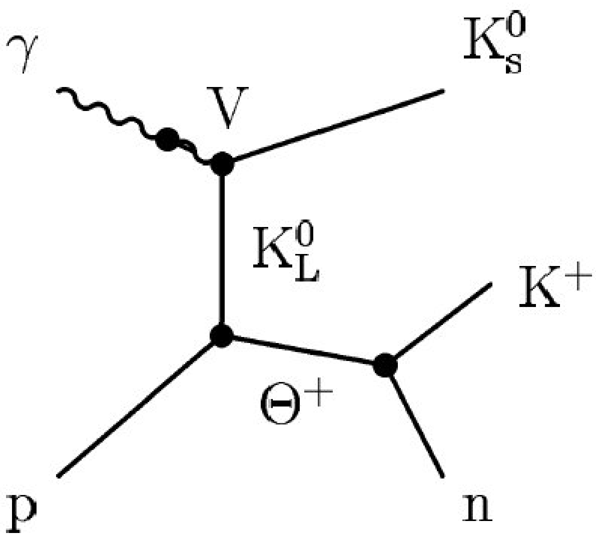


- Result of "g6a&b" analysis of channel $\gamma p \Rightarrow \pi^+ K K^+ (n)$
- Invariant mass of $\{K^+ n\}$ after selecting

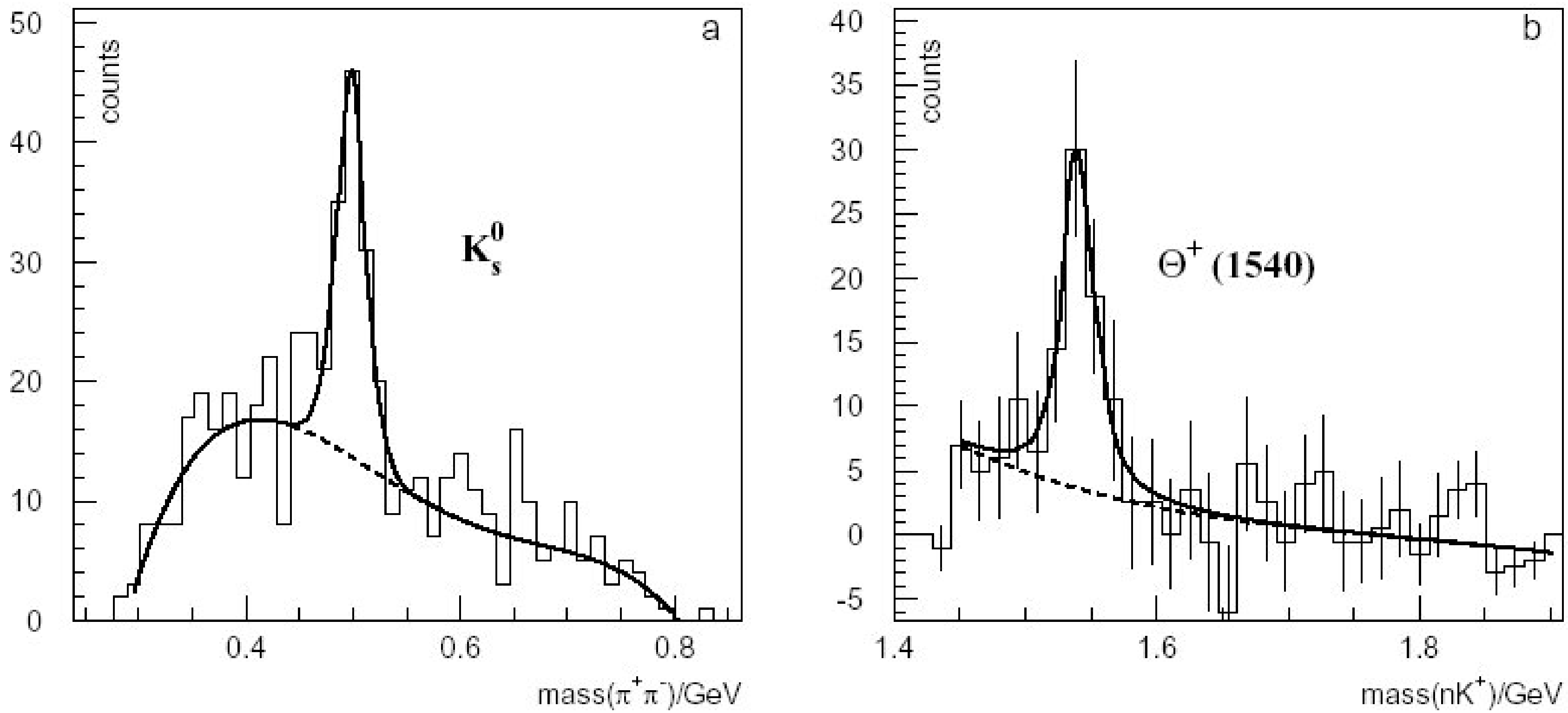
  $\cos \Theta^*(\pi^+ K^-) > 0.5$
- Background shape taken from spectrum without angle (small-*t*) cut
- Estimate 4.8 σ significance

Θ^+ photoproduction with the SAPHIR detector (Bonn)

- The reaction $\gamma p \Rightarrow \Theta^+ K_s^0$,
  where $K_s^0 \Rightarrow \pi^+\pi^-$
  and $\Theta^+ \Rightarrow nK^+$,
- Bremsstrahlung tagged photons have energy up to 2.6 GeV
- The neutron is identified in a kinematical fit



The SAPHIR result



- 1540 +/- 4 MeV, width < 25 MeV (90% CL)

Neutrino scattering

Courtesy of Dolgolenko (ITEP)

Reanalysis of bubble chamber experiments from WA21, WA25, WA59, E180, E632

$M(K_s p)$ spectrum

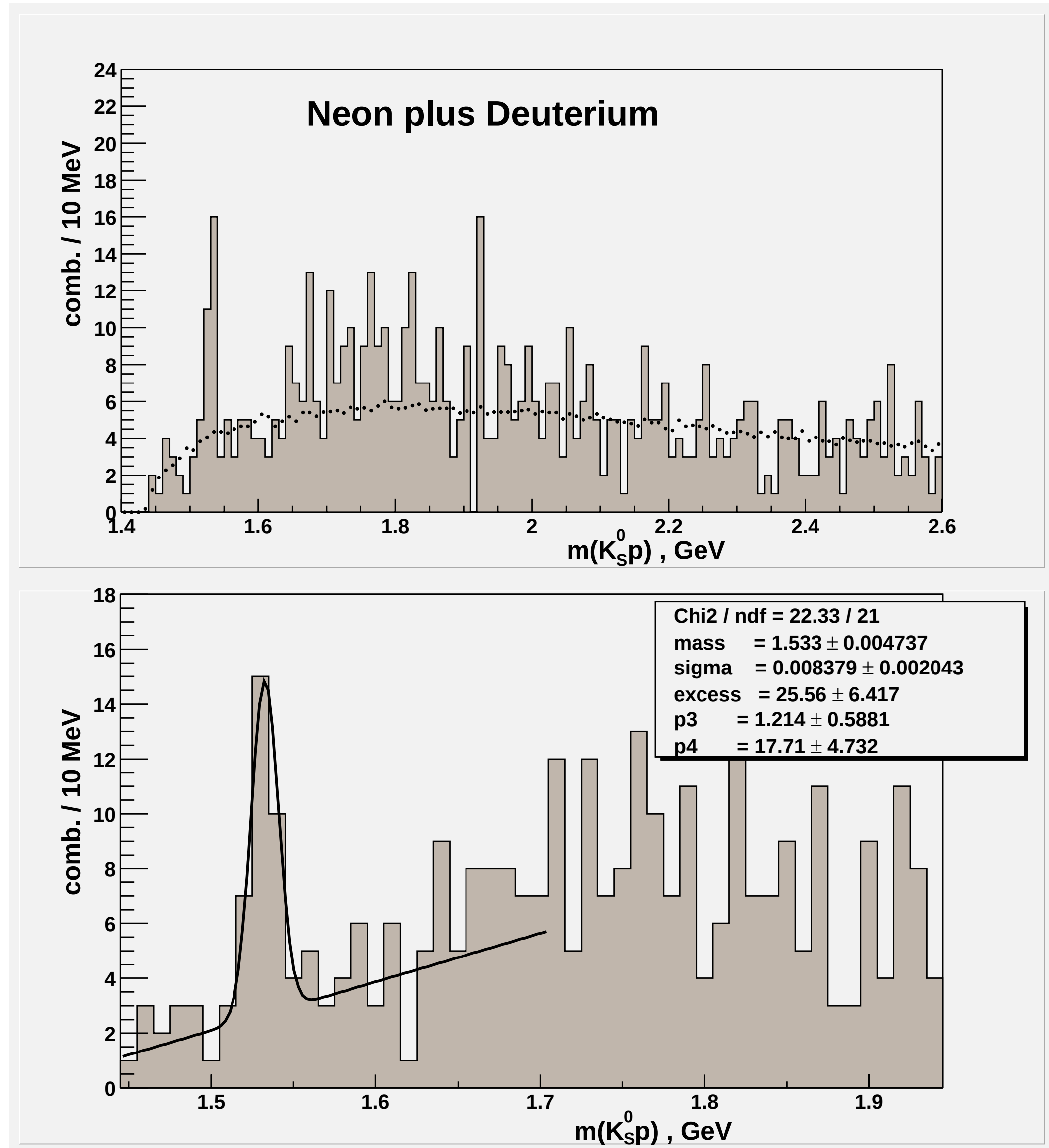


Figure 4: Invariant mass of the $K^0_S p$ system for the Neon and Deuterium data combined (top panel). The dots depict the random-star background. A fit of the same $m(K^0_S p)$

Additional questions

- The Θ^+ signal was observed on deuteron, nuclear targets, and proton experimentally.
- The existing information does not really answer questions required of a newly discovered subatomic particle:
  - Parity and spin
  - Isospin
  - Width (Lifetime)
  - Excited states
  - Form factors

Theoretical interpretations

- Chiral soliton model (Diakonov, Petrov, Polyakov) 1997:
  - the original motivation; Θ^+ is "rotational excitation" of soliton
- Flavor-spin quark interaction could lower the p-wave pentaquark state below the s-wave state (Stancu, Riska)
  - Assumes an s-wave NK^+ molecule would "fall apart"
- Diquark-triquark structure: 2 quasi-particle (Karliner, Lipkin)
  - Diquark (spin-0) and [diquark (spin-1) + s-bar] lower hyperfine
- Double diquark structure: $J^\pi = \frac{1}{2}^+$ (Jaffe, Wilczek)
  - Spin-0 diquarks act as pseudo-bosons and inhibit decay
- K^+N phase shifts reanalyzed (Arndt, Strakovsky, et al.)
  - Width of ~few MeV or less, or chi-square increases a lot
- Lattice Gauge calculation (Csikor, Fodor, Katz, Kovacs)
  - S=+1 pentaquark $J^\pi = (1/2)^+$ has mass 1.54 +/- 0.05 GeV
- Many others !!

What is next at CLAS?

- New data set being analyzed
  - Will double the statistics.
- New experiment E03-113 (Hicks/Stepanyan) approved by PAC, to run in February 2004
  - will provide 20x more statistics.
  - obtain angular distribution of the decay of Θ^+ as well as the energy dependence of the cross section.
- Continuing analysis effort with existing data

  $\gamma\, p \rightarrow K^0\, \Theta^+$ shows surprising cross section suppression

Exciting development if holds up!